DOE/MC/31174 -- 5189
(DE96004466)

Utilization of Low NO_X Coal Combustion By-Products

Quarterly Report
October - December 1995

January 1996

Work Performed Under Contract No.: DE-FC21-94MC31174

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Michigan Technological University
Houghton, Michigan

DISCLAIMER

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Morgantown, West Virginia 26507-0880

By
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1400 Townsend Drive
Houghton, Michigan 49931

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PROJECT SUMMARY - FIFTH QUARTER
October 1 through December 31, 1995

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PROJECT SUMMARY

Activities this quarter focused primarily on product development and technology transfer. Dewatering and drying studies were conducted. All of the product development subtasks are underway.

The technology transfer activities included:

- a presentation made by Mr. Richard Tieder at Michigan's Sixth Waste Reduction Roundtable in Lansing, Michigan. This presentation discussed the fly ash beneficiation process and the use of carbon from fly ash as a mercury sorbent for flue gas emission control.

- Dr. Jim Hwang gave a presentation to the Upgraded Coal Group in Pittsburgh, Pennsylvania, discussing a material perspective of fly ash. He described the use of materials processing technologies to convert fly ash to value-added, quality controlled, environmentally benign materials for an overall solution to fly ash problems.

- a presentation made by Ms. Allison Hein at the Upper Peninsula Recycling Coalition meeting in Marquette, Michigan. This presentation was a general overview of the various waste reduction and recycling research activities underway at IMP, including fly ash beneficiation and utilization. The IMP also had an exhibit table at the conference with photographs, handouts, and display items such as fly ash components, mullite, and fly ash/aluminum composite material.

- The Institute exhibited at the Michigan Recycling Coalition's 13th Annual Conference and Membership Meeting in Novi, Michigan. The exhibit included photographs, handouts, and display items such as fly ash components, mullite, and fly ash/aluminum composite material.

- The Institute exhibited at PowerGen Americas in Anaheim, California. The exhibit included photographs, handouts, and display items such as fly ash components, mullite, and fly ash/aluminum composite material.

TASK 1.0 - TEST PLAN

This task has been completed.

TASK 2.0 - LABORATORY CHARACTERIZATION

Task 2.1 - Sample Collection

A sample of low NOx fly ash has been received from Consumers Power Company.

Task 2.2 - Material Characterization

Characterization and analytical activities focused on the various utilization tasks and are detailed in the specific task descriptions. Characterization of the Consumers Power Company ash will begin next quarter.

Task 2.3 - Laboratory Testing of Ash Processing Operations

Laboratory activities this quarter centered primarily on the separation and dewatering of the clean ash fraction. Settling and leaf filter tests were conducted. A centrifuge was tested for dewatering the ash, and tests using a hydrocyclone to remove the fine fraction from the clean ash were conducted.

Settling Tests

A series of settling tests, to assist in the determination of thickener capacity requirements, have been carried out using both AEP and NPC ash and carbon fractions. These tests are used to establish the settling rates of each material at various pulp densities. This series of tests involved monitoring of a "mud line", which indicated the level to which the pulp had settled out, in a large graduated cylinder initially filled with a slurry of the material being tested. The solids content of the slurry was varied from 5% to 30% with each ash tested and from 5% to 15% for each carbon tested. A flocculant was also tested, which served to greatly reduce the time required for both the ash as well as the carbon to settle. In this series of tests, the flocculent was used in repeated tests involving the ash at 30% solids and the carbon at 15% solids.

Leaf Filter Tests

Leaf filter tests were initially conducted last quarter to assist in establishing capital cost estimates for a potential pilot plant operation. These tests involved a variety of filter media, form times, and drying times, as well as the addition of hot air (410F) and steam (300F) to assist in the removal of moisture from the ash being tested. From these tests, it was concluded that the addition of hot air or steam to the face of the cake during the drying period, although it served to reduce the final moisture slightly, would not be cost effective with the ash tested except in certain unique situations.

This quarter the leaf filter testing resumed and involved both a Class C (NPC) and a Class F (AEP) ash. A test matrix was put together and included form times of 5, 10, and 20 seconds, with drying times ranging from 30 to 360 seconds. Neither steam nor hot air were included in the testing. Data from these tests have been collected and compiled with the results indicating that, with the AEP ash a cake moisture of 17- 18% should be obtainable, whereas, with the NPC ash a cake moisture of 21 - 22% could be expected.

Centrifuge Tests

A series of tests using a centrifuge to dewater the ash were carried out during this quarter. The materials tested thus far included both as-received and clean fly ash from BGE and NPC. Other ashes, including DE and AEP will be tested as additional clean ash is generated in upcoming pilot plant runs. The results from the initial centrifuge tests indicate that final moisture levels for BGE ash would be expected to fall in the 10 - 11% range for both as-received and clean ash. The NPC as-received ash would be slightly higher, at just over 13% moisture.

An AML model 12-413V centrifuge incorporating a perforated bowl and a five micron filter cloth was used in the testing. The ash slurry, consisting of approximately one pound of ash being dispersed in about five gallons of water, was pumped into the system with a portion of the slurry being fed directly into the centrifuge and another fraction recirculating back into the original feed material. By constantly recirculating a portion of the slurry the dispersion of the ash was maintained and no ash was able to settle out. The operation of the centrifuge continued until the recirculating stream became clear. At that point the centrifuge was stopped and the cloth liner containing the ash cake was removed. The moisture of the cake was then determined using conventional means.

Hydrocyclone Tests

A number of preliminary hydrocyclone tests were run using AEP ash. These initial tests have proven that a hydrocyclone, although it may not offer the most accurate cut, may be used in the separation of the clean ash into various size fractions. Additional testing is to be carried out with the different parameters being varied to reduce the particle size of the fraction being carried out the overflow of the cyclone, while making a cleaner cut.

The fractions resulting from these hydrocyclone tests are then to be used in further centrifuge test. It is hoped that, with the separation of the coarse and fine fractions, the resulting moisture in each of the cakes produced in the centrifuge will be lower than that of the cake produced from the bulk clean ash. Both Class C and Class F ashes will be used in these tests.

TASK 3.0 - PILOT PLANT TESTING

No pilot plant tests were conducted during this quarter. Runs to generate clean DE2 ash, as well as additional AEP and NPC ash for block and brick testing will be conducted during the next quarter.

TASK 4.0 - PRODUCT TESTING

Activities are underway in all five subtasks. The concrete testing is winding down, with only one more clean ash remaining to test. Preliminary work in the concrete block and brick and the activated carbon tasks has begun. The metal matrix composite testing is producing some interesting results.

Task 4.1 - Concrete Testing

The compressive strength tests of concrete cylinder samples, with varied types and amounts of fly ash, are nearly finished, with the exception of DE2 clean ash, and the test results have been organized into tables. Also, the performance quality and workability during the concrete processing, eg. slump, air content, and density, have been organized into the tables. Detail analysis of the results, including statistical analysis, is in progress. The effect of different fly ash on concrete properties is described in the following sections. The tables referenced in the text are located in Appendix A.

Effect of AEP Ash on Concrete Property

The fly ash from America Electric Power Company's Appalachian Power Plant (AEP ash) is a Class F ash. The average LOI value of as-received AEP ash is 21.7%, which is much higher than the ASTM C 618 limit (6 wt%). After separation, a cleaned AEP fly ash has a 1.2% LOI value. The effects of as-received and cleaned AEP ash on concrete properties with a specific design strength of 3500 psi (35S) are shown in Tables 1 and 2, respectively. From Table 1, the concrete containing as-received AEP ash has a much lower air content in comparison to the concrete without the fly ash, and the water to cementitious material (W/C) ratio increases with the amount of cement replaced by fly ash while maintaining a desired slump value. Unlike the as-received fly ash concrete, the concrete containing cleaned ash keeps a high air content, and the W/C ratio decreases as the amount of cement replaced by fly ash increases, while maintaining a desired slump value (Table 2). Due to these characteristics, cleaned AEP ash, with a low LOI value, is more suitable for use in concrete. The 28 day compressive strength of concrete using both as-received and clean AEP ash satisfy design requirements. The effects of cleaned AEP ash on concrete properties with a specific design strength of 3000 psi (30S) and 4000 psi (40S) are shown in Tables 3 and 4, respectively. The same trend as occurred with 35S concrete can be observed from these tables. The 28 day compressive strengths of both 30S and 40S concrete containing cleaned AEP ash satisfy design requirements.

Effect of BGE Ash on Concrete Property

The fly ash from Baltimore Gas & Electric Company (BGE Ash) is also a Class F ash. The average LOI value of as-received BGE ash is 6.22%, which is higher than the ASTM C 618 limit (6 wt%). After separation, a cleaned BGE ash has a 1.3% LOI value. The effects of as-received and cleaned BGE ash on properties of 35S concrete are shown in Tables 5 and 6, respectively. From Table 5, the concrete containing as-received BGE ash has a much lower air content in comparison to the concrete without fly ash. The W/C ratio decreases with the increase in the amount of cement replaced by as-received BGE ash while maintaining a desired slump value. From Table 6, the air content of concrete containing cleaned BGE ash is also low in comparison to the concrete without fly ash, but much higher than the concrete containing as-received BGE ash. The W/C ratio decreases with the increase in the amount of cement replaced by cleaned BGE ash while maintaining a desired slump value. The 28 day compressive strengths of concrete using both as-received and cleaned BGE ash satisfy design requirements, with the exception of the concrete in which 40% of the cement was replaced by cleaned BGE ash.

Effect of NPC Ash on Concrete Property

The fly ash from Nevada Power Co. (NPC ash) is a Class C ash. The average carbon value of as-received NPC ash is 4.0%. A cleaned NPC ash has a 1.16% carbon value. The effects of as-received and cleaned NPC ash on properties of 35S concrete are shown in Tables 7 and 8, respectively. From Table 7, the concrete containing as-received NPC ash has a much lower air content in comparison to the concrete without fly ash. The W/C ratio decreases with the increase in the amount of cement replaced by NPC ash while obtaining a desired slump value. From Table 8, the air content of concrete containing cleaned NPC ash is also low in comparison to the concrete without fly ash, but higher than the concrete containing as-received NPC ash. The W/C ratio decreases with the increase in the amount of cement replaced by cleaned fly ash while maintaining a desired slump value. The 28 day compressive strength of concrete formed with both as-received or cleaned NPC ash satisfy design requirements, with the exception of concrete with 60% of the cement replaced by both as-received and cleaned NPC ash. The effects of cleaned NPC ash on concrete properties with a specific design strength of 3000 psi (30S) and 4000 psi (40S) are displayed in Tables 9 and 10, respectively. The same trend as occurred with 35S concrete can be observed from these tables. The 28 day compressive strengths of both 30S and 40S concrete containing cleaned NPC ash satisfy design requirements.

Effect of DE2 Ash on Concrete Property

The fly ash from Detroit Edison's River Rouge Unit #2 (DE2 ash) is a mixture ash containing approximately 70% Class F ash and 30% Class C ash, because the plant burns about 70% eastern coal and 30% western coal in its power generation. The effect of as-received DE2 ash on properties of 35S concrete is shown in Table 11. The concrete containing as-received DE2 ash has a low air content in comparison to the concrete without fly ash. The W/C ratio tends to decrease with the increase in the amount of cement replaced by DE2 ash while maintaining a desired slump value. The 28 day compressive strengths of the concrete containing as-received DE2 ash satisfy design requirements. Concrete testing with clean DE2 ash will get underway as soon as material is available.

Task 4.2 - Concrete Block/Brick

Concrete block and brick will be formed and tested at Alpena Community College in Alpena, Michigan. Preparation for the testing is in progress, including procurement of the raw materials, determination of ash needs, and machine testing.

Task 4.3 - Plastic Fillers

Discussion

We have concluded that it is not realistic to increase the brightness of clean fly ash by coating a white material on fly ash surfaces. This is based on our previous experimental results and information from a filler supplier saying that brightness is not a major factor for many filler applications. We decided to use the fine clean fly ash generated from the beneficiation process follwed by air classification for the plastic filler molding test.

The test started with the selection of polymer matrix materials and the coupling agent. We selected three different types of polymers and one corresponding coupling agent: polypropylene, low density polyethylene, high density polyethylene, and Z-6032 coupling agent. The fine clean fly ash was characterized according to standard plastic filler applications specifications. The fly ash was then mixed with the three polymers at various loading levels to make feed materials for injection molding. A total of fifteen batches of feed material have been produced. The procedure is given later in this narrative. Table 1 shows the characterization results of the fine clean fly ash and Figure 1 shows the morphology of the ash.

The next step is to conduct the injection molding tests. Tensile bars and hardness specimens will be produced to test the mechanical properties of the resulting products. The test procedures, describing the activities to date as well as the steps planned for the next quarter, are outlined as follows.

Table 1. Fine Clean Fly Ash properties

Properties	**AEP-C-4M**
Mean particle size, microns	4.13
Loose density, g/cc	0.804
Tap density, g/cc	0.874
Brightness	0.242
pH	6.6
Oil absorption	30

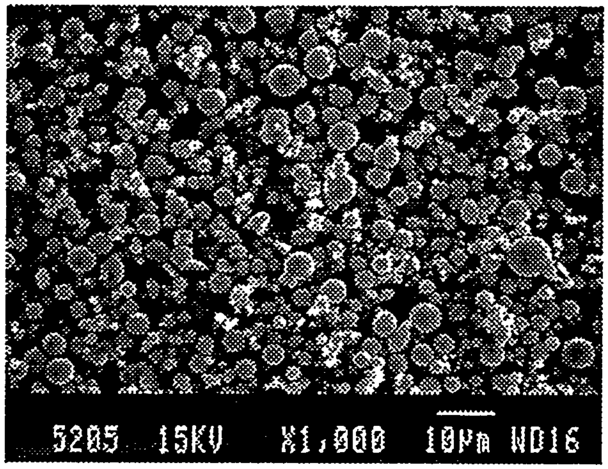

Figure 1. SEM morphology of 4 micron clean fly ash

Test Procedure

1. Raw materials

Plastics: Polypropylene homopolymer, T-3622, Fina
Low density polyethylene, Escorene LL6407.67, Exxon Chemical
High density polyethylene, HXM 50100, Phillips

Fine clean fly ash: 4 micron AEP clean ash (from pilot plant run#4)

Coupling agent: Dow Corning silane Z-6032

2. Fine clean fly ash preparation - Obtain three kilograms of 4 micron sized clean AEP fly ash by air classification of clean AEP ash.

3. Characterization of fine clean fly ash

a). Particle size and size distribution: by Microtrac

b). Particle shape: SEM pictures.

c). Loose density: Charge fly ash powder into a glass cylinder with volume scale. Weigh the powder: Loose Density = weight/loose volume

d). Tap density: Charge fly ash powder into a 100 ml glass cylinder, run the Stampvolumeter 100 times, record the final volume, and weigh the powder.
Tap Density = weight/tap volume

e). Brightness: Use the Zeiss Reflectance Photometer to measure the brightness

h). pH measurement: Measure the pH of deionized (DI) water first, and then disperse fly ash powder in DI water (about 30 wt% solid and 70 wt% water). Measure the pH of the slurry while stirring with a magnetic bar and stirrer.

f). Oil absorption: Follow the ASTM 281 standard

g). Chemical composition: ICP analysis

4. Surface treatment: Coat the fly ash powders with silane coupling agent.
Silane amount = 0.5 wt% of glass filler
Silane dilution: add 100 times distill water
Mix the silane solution with the fly ash powder for 10 minutes
Oven dry the slurry
Crush the coated fly ash powder through a 100 mesh (150 micron) screen.

5. Plastic and fly ash powder mixing:
Determine the weight for each mixing batch
Determine mixing temperatures for each type of plastic
Loading levels: 10 wt%, 20 wt%, and 40 wt% of fly ash powder in plastics.
Mixing: 50 RPM for 30 minutes

6. Injection molding and hardness tests:
Determine the molding temperature for each plastic mixture.
Determine the molding pressure, injection speed, and mold temperature for each mixture.
Produce tensile bars - five good pieces - for each batch of mixture.
Produce hardness specimen using the metallography press, three pieces for each batch.

7. Mechanical testing:
Test tensile strength, yield strength, Young's modules, and elongation using the Instron Mechanical Testing System.
Test hardness by a commercial lab.

8. Fracture surface observation: SEM pictures of one broken tensile bar from each batch.

Task 4.4 - Activated Carbon

A test apparatus has been fabricated for activating fly ash carbon. A preliminary test was run to check the suitability of this system. The resultant carbon will be evaluated to determine the adsorption properties such as BET surface area, iodine number, and molasses number.

The system consists of an activation bed, a heating furnace, and a gas-feeding unit. The activation bed is vertical and heated by the heating furnace. The temperature of the bed can be adjusted by the furnace controller. When steam is used as the activation gas, a syringe pump is used to feed water to the bed. The water is evaporated at high bed-temperatures, producing steam. The flow rate of steam is then obtained based on the water volume pumped to the bed and the bed temperature. When CO_2 is used, it is fed directly to the bed from a CO_2 gas cylinder through a pressure reducer.

Task 4.5 - Metal Matrix Composites

Activity in this task began this quarter. This task is being conducted in conjunction with a project, also funded by the DOE, to study aluminum/alumina composite shapes ("Low-Cost Aluminum Composite Shapes for Vehicle Applications", contract DE-FG48-95R810543). The data from that project will provide comparison information for the fly ash / aluminum composite materials.

Preliminary results of this investigation are very encouraging. Mechanical properties achieved using fly ash as a reinforcement are equivalent to that of typical aluminum powdered metal (PM). This material retained the ductility of the PM material which is unique for a ceramic reinforcement in a metal matrix composite (MMC) material. Processing of the material is comparable to PM. The spherical fly ash allows good flowability.

Accomplishments in this quarter began with obtaining the required materials, including 6092 aluminum powder and -635 mesh (20 micron) fly ash. The fly ash and aluminum were vacuum dried and blended to form a composite powder. Compaction pressure vs green density was measured, and the thermal behavior of the composite powder was examined using a Differential Scanning Colorimeter (DSC). Several outgassing/sintering practices were investigated and the optimum sintering procedure was identified. The microstructure of the sintered composite material was examined. A factoral design experiment was conducted to identify the optimum solution aging temperature and to determine the optimum aging time and temperature.

There was a problem heating the 6092 Al / fly ash composite material. An examination of the material, using SEM/EDS, found that the age hardening components of the 6092 alloy (magnesium and copper) were being absorbed by the fly ash.

Net shaped tensile bars were produced using the blending, outgassing/sintering, pressing, and heat treating procedures identified to date. The tensile bars were tested in accordance with ASTM E-8. A net shaped part (a monkey statue) was produced with 10 v/o fly ash.

Further work in this area will examine and solve the heat treat problem by changing alloy composition. The heat treat procedures will be re-evaluated. Another set of tensile bars will be produced to verify the material properties. Wear performance of the fabricated parts will be characterized. A demonstration component, probably bicycle idler gears, will be fabricated.

There is potential for using fly ash as a filler in PM materials. This new market could be developed to give fly ash a premium priced market place. Currently, 337,800 tons of iron powder is used per year, at an approximate cost of $600 per ton. The fly ash can be sold at $10/ton and replace approximately 10-15% of the iron PM market. This will make a significant decrease in the price of ferrous PM parts.

TASK 5.0 - MARKET AND ECONOMIC ANALYSIS

Plastic Fillers

Arrangements have been made with R.J. Marshall Company, Southfield, Michigan, a major processor and supplier of mineral fillers to the plastic resin industry, to evaluate the potential market acceptance of fly ash and components by the plastic industry.

Preliminary evaluations of recovered cenospheres, cleaned ash, and recovered carbon as mineral fillers indicate the materials generally qualify for use by the plastics industry. Primary qualifiers are specific gravity, oil adsorption, and, to a lesser extent, color. Additional cleaned ash samples from several utilities have been furnished Marshall for evaluation of ash consistency from source to source, i.e. the desirability of one ash over another.

Previous attempts by Marshall to sell fly ash into the plastics market has met with limited success because of inconsistent composition. A 2,000 pound cleaned ash sample from a single source has been requested by Marshall for extensive market evaluation.

Activated Carbon and Carbon Black

Carbon is the largest recovered fraction from beneficiated fly ash. Preliminary analyses suggests the carbon may have value as activated carbon, an absorber of select organic and metal species from air and water streams. Without further processing, the recovered carbon is between powdered and granular activated carbon in size. Each of these general forms find specific applications in waste water and gaseous effluent treatment.

Discussions have been held with a number of suppliers, processors, and consultants associated with activated carbon. In summary, the U.S. market for activated carbon is currently relatively small, 300 million pounds per year, growing at about 5% annually, and has come under considerable price pressure in recent years because of imports and major production in the Philippines, Indonesia, and China. In addition, one supplier indicated there is currently a glut of reactivated or secondary carbon on the market. Water treatment has been a significant user of activated carbon. That market is subject to Congressional changes in clean water legislation.

A potential large new market for activated carbon is the electric utility industry. Here the issues are possible legislated mercury control and treatment/disposal of mercury laden carbon. Future work on this aspect of the project will also focus on potential carbon markets other than activated carbon.

Capital Costs

Preliminary capital cost studies were compiled. Figures were generated for a one ton per hour ash beneficiation pilot plant, as well as a pelletizing operation of the same scale which could produce various size aggregate with or without pressurized curing in an autoclave.

APPENDIX A

Task 4.1 - Concrete Testing Tables

Table 1 - Effect of amount of cement replaced by as-received AEP fly ash on properties of 35S concrete (lb per cubic yard)*.				
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**
W/C ratio**	0.50	0.50	0.51	0.52
Cement, lb	564	517	451	395
Fly ash, lb	0	78	141	212
Water, lb	297	312	316	329
Fine Aggregate MC<0.5%	1150	1050	1014	939
Coarse Aggregate MC<1.0%	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.10
Slump, in	3.50	3.20	2.50	2.20
Air, (%)	7.10	2.00	1.80	1.90
pcf##	148.8	151.2	149.6	148.9
7 day strength, (psi)@	3692	4223	3357	2420
28 day strength, (psi)@	4676	5801	4582	3681
91 day strength, (psi)@	5512	6902	6201	5141

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data

Table 2 - Effect of amount of cement replaced by cleaned AEP fly ash on properties of 35S concrete (lb per cubic yard)*.						
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**	**20% Water reducer**	**30% Water reducer**
W/C ratio**	0.50	0.47	0.46	0.44	0.43	0.42
Cement, lb	564	517	451	395	451	395
Fly ash, lb	0	78	141	212	141	212
Water, lb	297	291	287	281	266	269
Fine Aggregate MC<0.5%	1150	1093	1098	1075	1155	1089
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845
Water Reducer, oz	0	0	0	0	17.80	32.10
AEA#, oz	9.90	10.60	10.90	11.10	10.90	11.10
Slump, inch	3.50	3.20	3.00	3.50	3.00	3.50
Air (%)	7.10	6.50	5.50	6.90	6.50	6.00
pcf##	148.8	145.4	145.8	144.2	146.6	144.8
7 day strength (psi)@	3692	3263	2561	2273	3103	2350
28 day strength (psi)@	4676	4446	4488	3681	4105	3392
91 day strength (psi)@	5512	6025	5442	4659	4977	4994

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
# Grace Daravair air entraining agent was used.
Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data

Table 3 - Effect of amount of cement replaced by cleaned AEP fly ash on properties of 30S concrete (lb per cubic yard)*.			
Amount replaced	**0% Mix1**	**20%**	**30%**
W/C ratio**	0.50	0.48	0.46
Cement, lb	494	392	343
Fly ash, lb	0	122	184
Water, lb	259	261	258
Fine Aggregate MC<0.5%	1331	1241	1205
Coarse Aggregate MC<1.0%	1845	1845	1845
Water Reducer, (oz)	0	0	0
AEA#, oz	8.80	9.24	9.50
Slump, in	2.50	4.00	3.25
Air, (%)	7.00	7.50	6.00
pcf##	146.4	145.3	144.4
7 day strength, (psi)@	3474	2385	1967
28 day strength, (psi)@	4158	3186	2774
91 day strength, (psi)@	4399	4547	4076

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.

Table 4 - Effect of amount of cement replaced by cleaned AEP fly ash on properties of 40S concrete (lb per cubic yard)*.				
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**
W/C ratio**	0.47	0.43	0.43	0.41
Cement, lb	610	545	489	428
Fly ash, lb	0	92	153	230
Water, lb	301	291	289	285
Fine Aggregate MC<0.5%	1094	1065	1040	1026
Coarse Aggregate MC<1.0%	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0
AEA#, oz	10.80	10.74	11.58	11.85
Slump, in	4.00	3.75	5.25	4.50
Air, (%)	5.50	7.50	9.00	6.00
pcf##	148.4	144.7	142.3	144.2
7 day strength, (psi)@	3981	3127	2609	2415
28 day strength, (psi)@	4823	3963	3545	3822
91 day strength, (psi)@	5412	5459	NA	4953

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.
NA Data not available

Table 5 - Effect of amount of cement replaced by as-received BGE fly ash on properties of 35S concrete (lb per cubic yard)*.					
Amount replaced	0% Mix1	8% Mix2	20%	30%	40%
W/C ratio**	0.50	0.47	0.48	0.47	0.47
Cement, lb	564	517	451	395	338
Fly ash, lb	0	78	141	212	282
Water, lb	297	297	299	302	309
Fine Aggregate MC<0.5%	1150	1095	1078	1025	971
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.10	11.40
Slump, in	3.50	3.50	2.20	3.00	3.00
Air, (%)	7.10	1.80	1.80	1.50	2.00
pcf##	148.8	152.2	151.5	151.3	149.4
7 day strength, (psi)@	3692	4482	3852	2968	2214
28 day strength, (psi)@	4676	6054	5383	4652	3634
91 day strength, (psi)@	5512	7173	6749	5899	4929

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data

Table-6 Effect of amount of cement replaced by cleaned BGE fly ash on properties of 35S concrete (lb per cubic yard)*.					
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**	**40%**
W/C ratio**	0.50	0.46	0.46	0.46	0.45
Cement, lb	564	517	451	395	338
Fly ash, lb	0	78	141	212	282
Water, lb	297	291	287	293	296
Fine Aggregate MC<0.5%	1150	1110	1098	1045	1000
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.10	11.40
Slump, in	3.50	3.20	2.20	3.00	4.00
Air, (%)	7.10	5.00	4.50	3.20	4.50
pcf##	148.8	147.4	148.3	147.8	145.1
7 day strength, (psi)@	3692	3322	2821	2468	1814
28 day strength, (psi)@	4676	4588	4158	3698	2921
91 day strength, (psi)@	5512	5453	4988	4682	4005

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
# Grace Daravair air entraining agent was used.
Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data

Table 7 - Effect of amount of cement replaced by as-received NPC fly ash on properties of 35S concrete (lb per cubic yard)*.							
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**	**40%**	**50%**	**60%**
W/C ratio**	0.50	0.47	0.46	0.45	0.42	0.42	0.40
Cement, lb	564	517	451	395	339	283	226
Fly ash, lb	0	79	141	211	283	353	424
Water, lb	297	297	287	286	277	279	276
Fine Aggregate MC<0.5%	1150	1092	1063	1064	1053	1002	968
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.09	11.36	11.62	11.86
Slump, in	3.50	3.50	4.00	3.50	3.25	3.75	4.00
Air, (%)	7.10	1.50	2.00	2.00	2.00	1.59	1.69
pcf##	148.8	152.8	151.8	151.6	150.9	151.4	151.2
7 day strength, (psi)@	3692	4393	4187	3657	3257	2344	1507
28 day strength, (psi)@	4676	6260	5992	5271	5277	4121	2980
91 day strength, (psi)@	5512	7304	7738	7326	7467	6302	5118

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.

Table 8 - Effect of amount of cement replaced by cleaned NPC fly ash on properties of 35S concrete (lb per cubic yard)*.							
Amount replaced	0% Mix1	8% Mix2	20%	30%	40%	50%	60%
W/C ratio**	0.50	0.46	0.44	0.43	0.43	0.42	0.41
Cement, lb	564	517	451	395	339	283	226
Fly ash, lb	0	79	141	211	283	353	424
Water, lb	297	287	277	274	280	283	283
Fine Aggregate MC<0.5%	1150	1094	1119	1090	1049	1007	974
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.09	11.36	11.61	11.86
Slump, in	3.50	3.50	3.75	3.00	3.25	2.00	2.25
Air, (%)	7.10	5.00	4.00	3.00	3.75	3.00	3.50
pcf##	148.8	147.6	149.0	150.8	147.1	143.4	146.4
7 day strength, (psi)@	3692	3557	3404	3298	2774	2044	1519
28 day strength, (psi)@	4676	4488	4929	4423	4399	3651	2684
91 day strength, (psi)@	5512	5833	6160	5624	5736	4735	4105

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.

Table 9 - Effect of amount of cement replaced by cleaned NPC fly ash on properties of 30S oncrete (lb per cubic yard)*.			
Amount replaced	**0% Mix1**	**20%**	**30%**
W/C ratio**	0.50	0.47	0.47
Cement, lb	494	392	343
Fly ash, lb	0	122	184
Water, lb	259	258	260
Fine Aggregate MC<0.5%	1331	1253	1207
Coarse Aggregate MC<1.0%	1845	1845	1845
Water Reducer, (oz)	0	0	0
AEA#, oz	8.80	9.30	9.50
Slump, in	2.50	2.50	3.50
Air, (%)	7.00	4.80	2.80
pcf##	146.4	149.2	148.7
7 day strength, (psi)@	3474	3021	2650
28 day strength, (psi)@	4158	4323	4205
91 day strength, (psi)@	4399	5977	5045

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.

Table 10 - Effect of amount of cement replaced by cleaned NPC fly ash on properties of 40S concrete (lb per cubic yard)*.				
Amount replaced	**0% Mix1**	**8% Mix2**	**20%**	**30%**
W/C ratio**	0.47	0.43	0.41	0.41
Cement, lb	610	545	489	428
Fly ash, lb	0	92	153	230
Water, lb	301	287	277	283
Fine Aggregate MC<0.5%	1094	1094	1081	1028
Coarse Aggregate MC<1.0%	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0
AEA#, oz	10.80	11.40	11.58	11.86
Slump, in	4.00	3.25	2.75	4.00
Air, (%)	5.50	4.57	5.25	3.90
pcf##	148.4	151.8	148.6	149.0
7 day strength, (psi)@	3981	3910	3864	3239
28 day strength, (psi)@	4823	4623	5118	5029
91 day strength, (psi)@	5412	5565	5683	6125

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.

Table 11 - Effect of amount of cement replaced by as-received DE2 fly ash on properties of 35S concrete (lb per cubic yard)*.						
Amount replaced	0% Mix1	8% Mix2	20%	30%	40%	50%
W/C ratio**	0.50	0.46	0.46	0.46	0.44	0.43
Cement, lb	564	517	451	395	339	283
Fly ash, lb	0	79	141	211	283	353
Water, lb	297	290	289	293	290	290
Fine Aggregate MC<0.5%	1150	1113	1099	1056	1023	982
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0	0
AEA#, oz	9.90	10.74	10.91	10.91	11.36	11.62
Slump, in	3.50	2.00	4.00	5.00	3.75	4.50
Air, (%)	7.10	4.50	3.60	4.00	2.80	2.50
pcf##	148.8	149.7	149.6	148.6	149.6	147.0
7 day strength, (psi)@	3692	3233	3522	3051	2845	2203
28 day strength, (psi)@	4676	5236	5253	5083	4870	4640
91 day strength, (psi)@	5512	NA	6160	6130	6172	5471

* Specified design strength is 3500 psi.
** W/C ratio = water/(cement + fly ash) ratio.
\# Grace Daravair air entraining agent was used.
\## Fresh unit weight (lb per cubic yard)
@ Compressive strength, psi, average of 3 data.
NA Data not available